In Situ Data Biases and Recent Ocean Heat Content Variability

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Abstract. The bulk of the recent global upper-ocean cooling signal between 2003 and 2005 reported by Lyman et al. (2006) is shown to be an artifact caused by a large cold bias discovered in a small fraction of Argo floats as well as a smaller but more prevalent warm bias in eXpendable BathyThermograph (XBT) data. These systematic data errors are shown to be significantly larger than sampling errors in recent years, and appear to be the dominant sources of error in estimates of globally integrated upper-ocean heat content variability. The bias in the XBT data is found to be consistent with errors in the fall-rate equations, suggesting a physical explanation for that bias. Finally, a revised estimate of upper-ocean ocean heat content suggests than no significant warming or cooling has occurred in recent years, with ocean heat content increasing by only 1 (± 16) $\times 10^{21}$ J between 2004 and 2006.

1. Introduction

As the Earth warms due to the buildup of greenhouse gasses in the atmosphere, the vast majority of the excess heat is expected to go toward warming the oceans (Levitus et al. 2005; Hansen et al. 2005). Changes in globally integrated upper ocean heat content anomaly (OHCA) therefore have very important implications for understanding the Earth's energy balance and the evolution of anthropogenic climate change. The observational record of OHCA appears to contain large interannual and decadal fluctuations that are not reproduced by recent coupled climate model simulations (Barnett et al. 2005). For instance, a large and apparently significant upper ocean cooling has been reported between 1980 and 1983 (Levitus et al. 2005). However, recent work suggests that a significant fraction of this cooling was caused by instrument biases in the in situ observing network (Gouretski and Koltermann 2007).

Another large and apparently significant cooling in OHCA between 2003 and 2005 was reported by Lyman et al. (2006). It has been suggested that this recent cooling could be attributed to a warm bias in eXpendable BathyThermograph (XBT) data and changes in sampling caused by the introduction of large amounts of data from the Argo array of profiling floats (http://www.argo.net) in the Southern Ocean (AchutaRao et al. 2007). However, an additional source of systematic data errors has been discovered in a small number of Argo floats. On balance, these instruments report temperature profiles that appear spuriously cold. In the present analysis, the cooling reported by Lyman et al. (2006) is shown to be an artifact caused by both the XBT warm bias and the cold bias in the Argo data. Estimates of the sampling error suggest that changes in data coverage did not contribute substantially to the spurious cooling despite the rapid introduction of new data in the Southern Ocean from the Argo array.

A description of the systematic errors in the Argo data as well as their cause and extent follows (Section 2). The warm bias in the XBT data during the period of the cooling is discussed, and a possible explanation for its cause is presented (Section 3). The effect of these biases on the OHCA estimate from 2004 through 2006 and a new estimate of OHCA for this period are also shown (Section 4), followed by discussions and conclusions (Section 5).

2. Argo Data Errors

In the OHCA estimate of Lyman et al. (2006), rapid cooling was exhibited in the tropical and subtropical Atlantic Ocean between 2003 and 2005. Comparison of individual temperature profiles with historical data in this region uncovered significant biases in profiles from a number of Argo floats (Figure 1). All of the affected profiles were found in Argo near real-time data, which had not undergone scientific quality control by the PI for these instruments.

The data error occurs in SOLO (Sounding Oceanographic Lagrangian Observer) instruments fabricated at WHOI (the Woods Hole Oceanographic Institution) and equipped with either FSI (Falmouth Scientific, Inc.) or SBE (SeaBird Electronics, Inc.) CTD (Conductivity-Temperature-Depth) sensors. Further investigation of the data returned by these instruments uncovered a flaw that caused temperature and salinity values to be associated with incorrect pressure values. Almost all of the WHOI FSI floats (287 instruments) and approximately half of the WHOI SBE floats (about 188 instruments) suffered from errors of this nature.

From Jan. 1, 2000 through June 30, 2007, the WHOI FSI floats produced approximately 20,000 profiles, almost all of which contain spurious pressure values. During the same period, WHOI SBE floats produced approximately 14,800 profiles, about 7000 of which had pressure errors. These 30,000 spurious profiles account for about 8 % of the total number of Argo profiles during this period.

Although errors in the affected profiles varied depending on float configuration, their net effect was to produce a strong cold bias at depth. A regional mean of temperature differences between the affected profiles and climatological temperature from the WOCE Global Hydrographic Climatology (WGHC, Gouretski and Koltermann 2004) illustrates this (Figure 2). In contrast, the mean temperature anomaly based on non-WHOI float data from the same region and time is smaller and positive. Data used in Figure 2 were restricted to the Atlantic Ocean between 50°S and 50°N and from Jan. 1, 2003 to June 30, 2007. This subset includes about 23,000 of the biased profiles, and about 33,800 profiles from non-WHOI floats.

The cold bias is greater than -0.5°C between 400 and 700 m in the average over the affected data and has a vertical structure that is similar to the cooling discussed in Lyman et al. (2006). This is due primarily to the WHOI FSI floats, which assigned incorrect pressure values that were predominantly biased shallow. Pressure offsets in the affected WHOI SBE profiles were somewhat smaller and changed sign depending on depth and float configuration.

It is important to note that these systematic errors were caused by improper processing of float data, and they do not reflect an inherent flaw in the instruments. As a result, about one-half of the affected profiles will be corrected exactly and the remainder will be corrected to a good approximation. Corrected profiles should be uploaded to the Global Data Archive Centers by October 31, 2007, and users who download these data subsequent to that date should receive the corrected versions (W. B. Owens and C. Schmid, personal communication 2007). Until then, these data cannot be easily repaired by the end user because correction requires additional information reported by the floats, and is not a uniform offset over entire profiles. Therefore, these profiles should be excluded from scientific analyses that may affected by pressure errors until corrected profiles become available. The biased WHOI floats can be identified by their individual WMO identification numbers, found in the Argo variable "PLATFORM_NUMBER". A list of the WMO numbers for all affected floats has been published on the internet (see http://www.argo.ucsd.edu/ for these WMO numbers and more details).

3. XBT Instrument Bias

Although XBT profiles account for a large fraction of historical ocean temperature data since the late 1960s, these inexpensive instruments were not designed to provide climate-quality scientific data. These probes do not measure pressure or depth, but instead record temperature as a function of time since the probe entered the water. They are designed to fall at a known rate, and fall-rate equations are used to convert elapsed time into depth. The existence of systematic errors in the fall-rate equations provided by the manufacturer have been known for some time and new fall-rate equations as well as a correction factor for old XBT data have been estimated (Hanawa et al. 1995). Both here and in Lyman et al. (2006), the corrections recommended by Hanawa et al. (1995) were applied.

However, recent reports of time-dependent temperature biases in the XBT data (Gouretski and Koltermann 2007; AchutaRao et al. 2007) suggest that systematic errors in the fall-rate equations may remain. Errors in the fall-rate equations result in temperatures that are assigned to the incorrect depth. If temperature biases observed by these authors are related to the fall rate equations, then these biases will be better explained by considering isotherm displacements, as attempted here.

For the data used by Lyman et al. (2006), isotherm displacements were computed relative to the local temperature climatology as follows: $Z = (T - T_{clim}) / (\partial T_{clim} / \partial z)$. Here T is observed temperature, T_{clim} is local climatological temperature from WGHC and dT_{clim}/dz is the vertical temperature gradient, also computed from climatology. In order to test whether warm biases in recent XBT data are consistent with a fall-rate error, XBT profiles are compared with nearby Argo temperature profiles (excluding data from all affected WHOI floats).

XBT/Argo pairs are defined to be within 4° longitude, 2° latitude, and 90 days in time. This results in about 23,400 pairs from 2003 through the end of 2006. Regions with vertical temperature gradients smaller than 0.002°C/m were excluded. Median differences between isotherm displacements computed from nearby XBT and Argo profiles strongly suggest fall-rate errors (Figure 3). The isotherm displacements derived from XBT probes are systematically deeper than Argo displacements by about 2% in the median. The fact that this discrepancy approaches zero near the surface (outside of the mixed layer) and increases linearly with depth suggests that the XBT bias is related to incorrect calibration of the fall-rate equations, rather than an actual bias in temperature.

A similar comparison between isotherm displacements from Argo (excluding WHOI float profiles) and CTD pairs from Jan. 1, 2000 through Dec. 31, 2006 (Figure 3) shows no such pattern. Only about 2,000 Argo/CTD pairs were available, resulting in a somewhat noisier estimate. However, the difference between displacements computed from nearby CTD and Argo profiles is close to zero over most of the depth range analyzed. The only range with large differences encompasses the surface mixed-layer, where vertical temperature gradients can be small and temporal variations are large. These two factors make the near-surface results noisy. The Argo/CTD comparison suggests that once the WHOI float profiles have been removed, the remaining systematic errors in the Argo data are much smaller than systematic errors in the XBT data.

Thus in the aggregate during the study period, XBT probes assign temperatures to depths that are about 2% too deep (Figure 3). It is important to note, however, that the median values presented here represent an average over many different types of XBT instruments. Previous authors have shown that fall-rate errors may vary depending on probe type (Hanawa et al. 1995) and manufacturer (Kizu et al. 2005a, 2005b). Furthermore, misapplication of corrections to fall-rate errors has compounded such problems in the past (Willis et al. 2004; Lombard et al. 2004). Therefore, application of any depth correction on the basis of this result alone is not recommended. Further analysis of the XBT bias is required before it can be adequately addressed. Errors must be characterized considering factors such as probe type, manufacturer, adjustments to probe design, and changes in fabrication materials and methods.

4. Recent OHCA Variability

The effects of the systematic data errors discussed above on OHCA between 2004 and 2006 are demonstrated using subsets of the profile data (Figure 4). These estimates were computed by integrating over maps of OHCA made using the techniques and mapping parameters described by Willis et al. (2004). The error bars shown in Figure 4 are computed using altimeter data (Ducet et al. 2000) and represent sampling error only, computed as in Lyman et al. (2006). Because their wavenumber and frequency characteristics are almost identical to those of upper ocean temperature variability (Zhang and Wunsch 2001), the altimeter data provide an excellent means of testing the skill of the mapping technique. Additional uncertainties, however, may arise from instrument biases, inaccuracies in the climatology, aliasing of the seasonal cycle, or other errors.

The OCHA estimate made using all data including spurious float profiles (thick solid line) shows an apparent cooling of 45×10^{21} J (48 zetajoules) from 2004 to 2006. Another estimate using all data except the spurious float profiles (thick dashed line) suggests much less cooling, only about 14 zetajoules. More than half of this erroneous cooling arises because of the increasing fraction of spurious profiles in the Argo data stream produced by the WHOI floats, primarily the floats with FSI instruments.

The effect of the XBT bias is demonstrated by making OHCA estimates from two more subsets of the data. One is made by excluding all Argo float data (thin dashed line), and consists primarily of XBT profiles that are uncorrected for the fall-rate bias shown in Figure 3. The other is made using only Argo data but excluding the spurious WHOI float profiles (thin solid line). Here all OHCA estimates are plotted relative to the same mean, whereas in Lyman et al. (2006, their Figure 1), record-length means were subtracted from the two different OHCA estimates before plotting.

The Argo-only estimate (excluding all affected WHOI float profiles) shows about 1 (± 16) zetajoules of warming between 2004 and 2006. As the systematic biases in the XBT data cannot yet be accurately removed, this estimate of OHCA variability is the most robust during this short period. Although neither the XBT-only nor the Argo-only estimate shows significant warming or cooling during this period, they are separated by approximately 73 zetajoules, consistent with the XBT bias discussed in Section 3. The reason for the small apparent cooling in the estimate that combines both XBT and Argo data (thick dashed line) is the increasing ratio of Argo observations to XBT observations between 2004 and 2006. This changing ratio causes the combined estimate to exhibit cooling as it moves away from the warm-biased XBT data and toward the more neutral Argo values.

5. Discussions and Conclusions

Systematic pressure errors have been identified in real-time temperature and salinity profiles from a small number of Argo floats. These errors were caused by problems with processing of the Argo data, and corrected versions of the affected profiles will soon be supplied by the float provider. Until corrected profiles are available, however, these data may be unsuitable for many oceanographic analyses. Recent scientific results that relied heavily on real-time Argo data in the tropical and subtropical Atlantic downloaded prior to October 31, 2007 may require re-examination for sensitivity to these errors. Argo data users should be aware that only delayed-mode quality controlled data have been examined by the float providers.

Most of the rapid cooling reported by Lyman et al. (2006) has been demonstrated to be the result of both the cold bias in the spurious Argo data and the transition from an ocean observing system dominated by warm-biased XBT data to one dominated by Argo data. Furthermore, these systematic errors are shown to be significantly larger than sampling error in the recent OHCA estimate. This suggests that sparse sampling in the Southern Ocean was not the primary cause of the spurious cooling.

OHCA does not appear to exhibit significant warming or cooling between 2004 and 2006. However, without fully addressing the XBT bias, it does not seem prudent to combine XBT data with data from the Argo array. Furthermore, only in 2004 does Argo coverage become adequate to determine the global integral without including XBT profiles. For these reasons, OHCA variability is not estimated prior to 2004 in the present analysis.

Here errors in the fall-rate equations are proposed to be the primary cause of the XBT warm bias. For the study period, XBT probes are found to assign temperatures to depths that are about 2% too deep. In the global integral, this fall-rate error is consistent with results here that XBT-based OHCA estimates are biased warm by about 73 zetajoules relative to Argo-based estimates during this period. However, further characterization of the XBT bias will be necessary before this error can be fully corrected.

The absence of a significant cooling signal in the OHCA analyses presented here brings estimates of upper-ocean thermosteric sea level variability into closer agreement with altimeter-derived measurements of global mean sea level rise. This implies a much less dramatic increase in the melting of land-bound ice that would be necessary to close the sea level budget (Willis et al. 2007)

Finally, recent variability in OHCA does not appear to be outside the range of fluctuations simulated by coupled climate models (AchutaRao et al. 2006; Barnett et al. 2005). The 1980-83 60-zetajoule cooling in the globally integrated OHCA record (Levitus et al. 2005) is significantly reduced when instrument biases are taken into account (Gouretski and Koltermann 2007). Similarly, the previously reported cooling beginning in 2003 (Lyman et al. 2006) has been shown here to be the result of instrument biases. The reduction or removal of these cooling events reduces decadal variability in the observed global integral of OCHA. For this reason, the observational record of globally integrated OHCA should not be used to evaluate decadal variability in coupled climate models until the XBT bias has been addressed fully.

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Figures

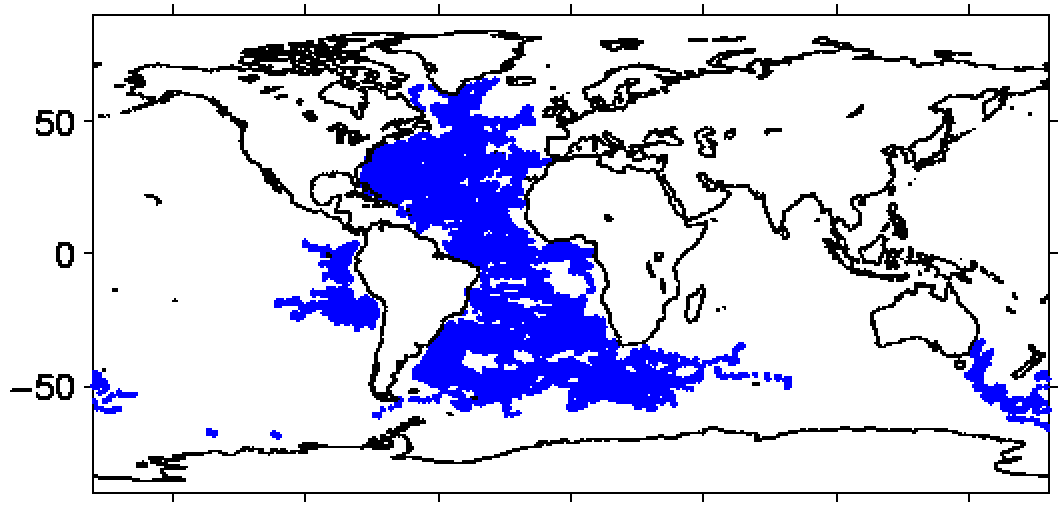

Figure 1. Distribution of profiles from WHOI floats with spurious pressure values reported from January 1, 2003 through June 30, 2007.

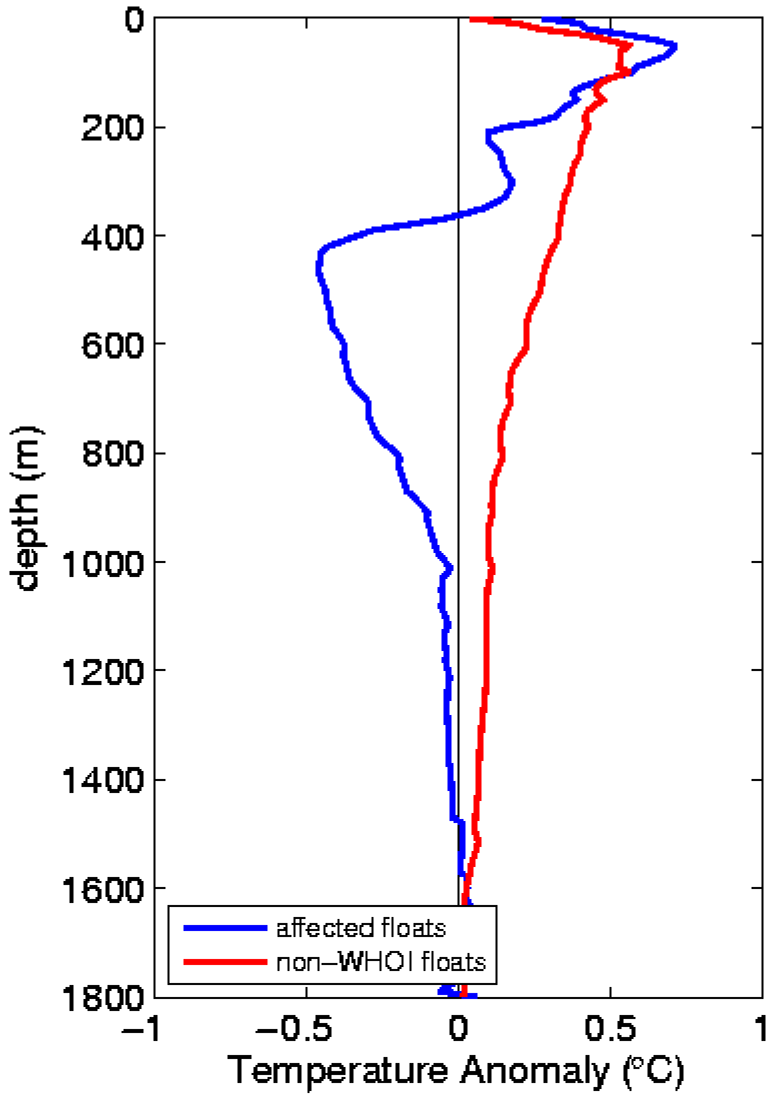

Figure 2. Temperature anomaly versus depth relative to the WGHC for WHOI floats with incorrect pressure values (blue line) and non-WHOI floats from the same region (red line). Data were restricted to the Atlantic and to latitudes between 50°S and 50°N from Jan. 1, 2003 through June 30, 2007.

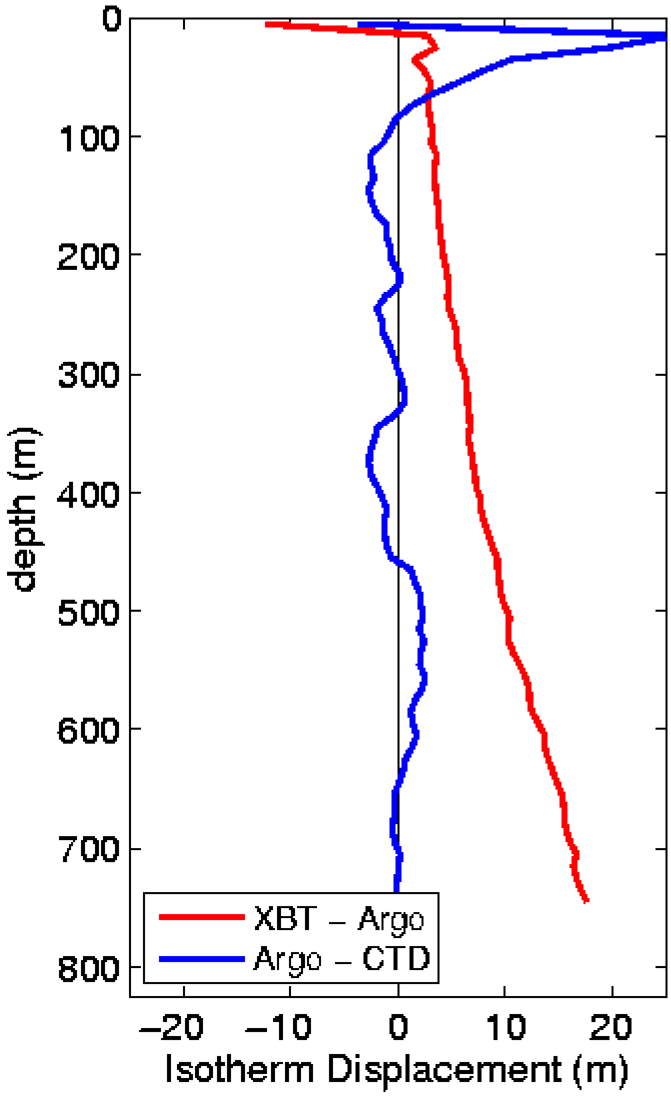

Figure 3. Median difference between isotherm displacements computed from 23,400 nearby XBT and Argo pairs collected between Jan. 1, 2003 and Dec. 31, 2006 (red line). Also shown is the median difference between isotherm displacements computed from 2,000 nearby CTD and Argo pairs collected between Jan. 1, 2000 and Dec. 31, 2006 (blue line). All WHOI floats were excluded from this analysis. Positive displacements reflect deeper isotherms.

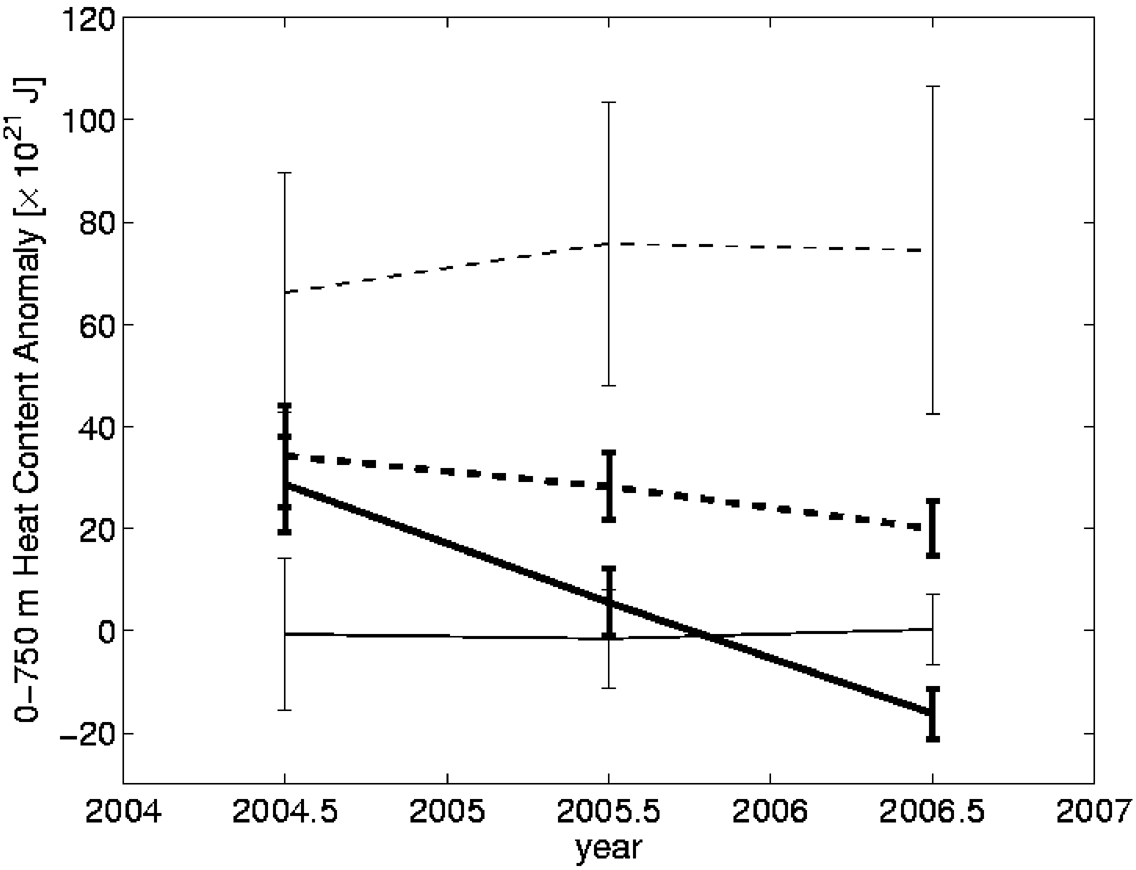

Figure 4. Annual values of globally integrated OHCA in the upper 750 m using all available data (thick solid line), using all data except profiles from WHOI floats with spurious pressure values (thick dashed line), using only Argo data except profiles from affected WHOI floats (thin solid line), and using no Argo data (thin dashed line). As in Lyman et al. (2006), error bars reflect only sampling errors and not the complete error budget.